CYCLONE PERFORMANCE FOR REDUCING BOICHAR CONCENTRATIONS IN SYNGAS

A Thesis

by

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ABSTRACT

Cotton gins have a readily available supply of biomass that is a by-product of cotton ginning. A 40 bph - cotton gin processing stripped cotton must manage 2,600 to 20,000 tonnes of cotton gin trash (CGT) annually. CGT contains approximately 16.3 MJ/kg (7000 Btu/lb.). CGT has the potential to serve as a renewable energy source. Gasification of biomasses such as CGT can offer processing facilities the opportunity to transform their waste biomass into electricity. The gasification of CGT yields 80% synthesis gas (syngas) and 20% biochar. The concentration of biochar in the syngas needs to be reduced prior to the direct fueling of an internal combustion engine driving a generator for electricity production. It was estimated that direct fueling of an internal combustion engine with syngas to drive the generator to produce electricity would cost $1M per megawatt (MW). In contrast, a 1MW system that consists of a boiler and steam turbine would cost $2M/MW.

The current provisional patent for the TAMU fluidized bed gasification (FBG) unit uses a 1D2D and 1D3D cyclone for the removal of biochar. A cyclone test stand was designed and constructed to evaluate cyclone capture efficiencies of biochar. A statistical experiment design was used to evaluate cyclone performances for varying concentrations of biochar. A total of 24 tests for the 1D2D and 36 tests for the 1D3D cyclone were conducted at ambient conditions. Average collection efficiency for the 1D2D cyclone was 96.6% and 96.9% for the 1D3D cyclone. An analysis on the cyclone's pressure drop was performed to compare the change in pressure drop from air only passing through the cyclone and when the cyclones are loaded with biochar. The average change in pressure drop for the 1D2D cyclone was a decrease of 74%, and the average change in pressure drop for the 1D3D cyclone was a decrease of 36%.

An economic feasibility study was conducted to determine the price per kWh to produce electricity for a CGT fueled internal combustion engine power plant (ICPP) and a boiler and steam turbine power plant (SPP). The simulated cotton gin is a 40 bph rated facility operating for 2,000 hours a season (200% utilization) processing stripped cotton that yields approximately 180 kg/bale (400 lbs/bale) of CGT. Revenues consist of the electricity and natural gas expenses incurred during the ginning season, along with the extra electricity produced and sold back to the utility company at the whole price. Loan payments and operating costs include labor, maintenance, taxes, and insurance. Labor costs, the selling price of electricity and biochar are varied in the economic model. The ICPP has a NPV of $1,480,000, and the SPP has a NPV of -$160,000, under the base assumptions. The sensitivity analysis resulted in the selling price of electricity as having the largest change on the NPV for both of the power plants. The average predicted purchase price of electricity is $0.10/kWh for the twenty year simulation. The average price to produce electricity, with no source of revenue generation for the ICPP is $0.20/kWh and $0.26/kWh for the SPP.

DEDICATION

This thesis is dedicated to my parents, Dr. Parnell, Russell McGee, and my friends for their endless support.

ACKNOWLEDGEMENTS

One's personality, dedication, and internal drive are a result of those who have influenced their life at one point in time or another. I would first like to thank my parents who have provided unconditional love and support since the day I was brought into this world. Without them, I would not be the person that I am today.

The saying "it takes a whole village to raise a child" applies not only to my family, but to my fraternity brothers and friends that I acquired during my collegiate career. My brothers have been a vital influence during a crucial time in a young man's life.

Dr. Calvin B. Parnell and Russell McGee are two individuals who I owe due credit to for my intellectual and professional development. Mr. McGee is the man who provided me with the opportunity to work as an undergraduate student worker, which developed into a graduate assistantship under Dr. Parnell. Both of these men have endured my stubbornness and other undesirable qualities. At times they may have given up hope, yet their patience and support prevailed.

Special thanks go to my fellow employees in the CAAQES lab, especially Daniel Luehrs. Daniel spent countless hours during the miserable Texas summers providing support to aide myself in the completion of my experiments. This thesis would not be possible without the support from all of the faculty, staff, and employees in the Department of Biological and Agricultural Engineering.

NOMENCLATURE

ΔP	Pressure Drop
%U	Percent Utilization
AED	Aerodynamic Equivalent Diameter
ANOVA	Analysis of Variance
BG	Bales Ginned
bph	Bales Per Hour
CAA	Clean Air Act
CCD	Classical Cyclone Design
CFPP	Coal Fired Power Plant
CGT	Cotton Gin Trash
DB	Declining Balance
dscm	Dry Standard Cubic Meter
EIA	United Stated Energy Information Administration
EPA	Environment Protection Agency
ER	Equivalence Ratio
FBG	Fluidized Bed Gasification
GR	Rated Capacity
GSD	Geometric Standard Deviation
ICPP	Internal Combustion Engine Power Plant

IRS	Internal Revenue Service
K	Constant For Cyclone Pressure Drop Calculations
L	Season Length
LCV	Low Calorific Value
LFE	Laminar Flow Element
M.W.	Molecular Weight
MARCS	Modified Accelerated Cost Recovery System
MC	Mass Captured
MI	Mass Placed Into Hopper
microns	micrometers
MJ	Mega joule
MMD	Mass Median Diameter
MR	Mass Remaining in Hopper
MW	Megawatt
NAAQS	National ambient Air Quality Standards
PM	Particulate Matter
PSD	Particle Size Distribution
SPP	Boiler and Steam Turbine Power Plant
STP	Standard Temperature and Pressure
syngas	Synthesis Gas
TAMU	Texas A&M University
TCD	Texas A&M University Cyclone Design

TCGA	Texas Cotton Ginners Association
V_i	Inlet Velocity
V_o	Outlet Velocity

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The Clean Air Act amendment of 1970 (CAA) passed by Congress authorized the Environmental Protection Agency (EPA) to develop federal regulations to limit emissions from both stationary and mobile sources. Under the 1970 CAA, one of the four regulatory programs created was the National Ambient Air Quality Standards (NAAQS). The NAAQS was last updated in the amendments made to the CAA in 1990, where pollutants considered being harmful to the public health and environment are regulated. The criteria pollutants that are regulated include Carbon Monoxide (CO), Particulate Lead (Pb), Nitrogen Oxides (NO_x), Ozone (O_3), particulate pollution ($PM_{2.5}$ and PM_{10}), and Sulfur Dioxide (SO_2). Greenhouse gasses (GHG) were not listed under the NAAQS's regulated pollutants as pollutants that were considered harmful to the public's health or the environment.

The EPA recently attempted to pass a Cap and Trade Bill to regulate emissions of GHG produced by stationary and mobile sources. Carbon Dioxide (CO_2) is considered one of the largest emitters of GHG in the United States and a major contributor to global warming. Coal-Fired Power Plants (CFPP) account for 42% of the United States' electricity generation (EIA, 2013), as well as 82% of the U.S.'s CO_2 emissions from electricity generation (EIA, 2008). Regulations such as the Proposed Cap and Trade Bill for GHG could pose a potential threat to shutting down CFPP and limiting the amount of available electricity produced. Such regulations have the potential for a hierarchy to be placed on the distribution of electricity. Rural agricultural operations such as cotton gins could be faced with limited supplies of electricity due to potential political priorities favoring voters in populated urban areas.

A five-year survey on Texas cotton gin's average operating costs was performed by Texas Cotton Ginners Association (TCGA) for the 2007-2012 ginning seasons (TCGA, 2013). The average cost per bale of ginned lint was $3.74 for electricity, $1.02 for gas, and $6.66 for labor. A simulated 40 bale-per-hour (bph) gin operating for 2,000 hours in a season has the potential to process 64,000 bales of lint. The total energy costs for the 64,000 bales are estimated to be $304,600. Cotton gin managers are always searching for means to lower their operating cost for each bale of cotton processed.

There are three cotton harvesting methods in Texas. Picked cotton contains the least amount of cotton gin trash (CGT) with approximately 45 to 70 kg/bale (100 to 150 pounds per bale (lbs./bale); stripped with field cleaners with approximately 180 kg/bale (400 lbs./bale) and stripped without field cleaners with 350 to 450 kg/bale (800 to 1000 lbs./bale). CGT contains approximately 16.3 mega joules per kilogram (MJ/kg) (7000 Btu/lb.). The cotton gin manager must manage the large mass of CGT. A 40 bph - cotton gin processing stripped cotton, operating for 2,000 hours/season must manage 11,600 tonnes of CGT annually (Saucier, 2011). The costs associated with handling CGT are significant.

CGT has the potential to serve as a renewable energy source. However, CGT is similar to many agricultural biomasses in the CGT ash has a low melting point (low eutectic point). Biomasses with low eutectic points have inherent problems when used as fuels for combustion systems. The slagging and fouling prevents sustainable operation. A sustainable thermo-chemical capture of the energy in the trash has the potential to reduce a cotton gin's operating costs.

In contrast to combustion, fluidized bed gasification (FBG) is a method that can be used to reliably capture the energy in the biomass with low eutectic points. Gasification is a thermo-chemical reaction in an oxygen deprived environment. FBG will yield a low calorific value (LCV) gas know as synthesis gas (syngas) and biochar. The biochar are the solids resulting from gasification. Gasification of CGT will typically yield 80% syngas (LCV gas) and 20% solids (biochar). The syngas will have an approximate energy content of 5,600 kJ/dry standard cubic meter (dscm) (Capareda, 2010). The goal of this research is to use the syngas to fuel a generator for electricity production.

The first patent for the Texas A&M University (TAMU) FBG unit was awarded in 1989 (LePori and Parnell, 1989). In the patent, biomasses are gasified to produce syngas. The biochar laden syngas passes through a 1D3D and 1D5D cyclone in a series connection for the removal of biochar. The syngas is used to fuel a boiler and steam turbine to generate electricity.

Advancements in the TAMU FBG unit resulted in a provisional patent in 2010 (Capareda et al, 2010). The improved design of the gasification unit produced a syngas with higher energy content. The biochar is conveyed by the syngas to a 1D2D followed by a 1D3D cyclone in a series. It was estimated that direct fueling of an internal combustion engine with syngas to drive the generator to produce electricity would cost

$1M per megawatt (MW). In contrast, a 1MW system that consists of a boiler and steam turbine would cost $2M/MW. Cotton gins possess a unique opportunity for the utilization of gasification technology as they have a readily available supply of biomass produced from cotton ginning.

Wang (2004) describes the Classical Cyclone Design (CCD) and the TAMU cyclone design (TCD) methods used to design cyclones. The CCD method is also described in Cooper and Alley (2008). The differences between the CCD and TCD methods are as follows:

1. The CCD design method does not base the dimensions on inlet velocities. The TAMU method sizes the cyclone based upon design inlet velocities.
2. The CCD method uses a flawed efficiency equation developed by Lapple (1951). Results of recent studies (Faulkner, 2008) have shown that the TAMU method more accurately predicts the cyclone efficiencies.
3. The pressure drop calculation using the CCD method requires the designer to select a "K" value based upon the desired cyclone. The TAMU method for calculating ΔP utilizes inlet and outlet velocity pressures and an empirical parameter.

Stevens (2001) reported on the design methods used for hot gas conditioning for large scale biomass gasification systems. In the study, particulate removal technologies were evaluated for the cleaning of syngas. Stevens indicated that cyclones were an effective means of particulate separation from syngas while being relatively inexpensive to operate and construct. Capture efficiencies of 90% and higher were common with particulate larger than five micrometers (μm). LePori and Soltes (1985) reported cyclone efficiencies for the separation of biochar from syngas from the initial gasification system. The separation of biochar from the syngas stream was accomplished with TAMU 1D3D and 1D5D cyclones in series. The reported efficiencies approached 97% for removing biochar concentrations from the syngas.

Improvements were made to the original TAMU FBG unit resulting in a provisional patent in 2010 (Capareda et al, 2010). The biochar for this provisional patent system had different physical characteristics. It was uniform compared to the large biochar particles reported by LePori and Soltes (1985). Syngas with an approximate energy content of 5.6MJ per dry standard cubic meter (MJ/dscm) was obtained with the improved design. The new gas clean up system consisted of 1D2D and 1D3D cyclones in a series. Saucier (2012) reported preliminary performance data for the 1D2D and 1D3D cyclones in series. This system had an average capture efficiency of 97%.

Simpson and Parnell (1996) reported efficiencies for the 1D2D and 1D3D cyclones of 99%. These experiments used particulate matter (PM) found in agricultural industries with typical concentrations of 6 g/m^3. These prior tests concentrations were much lower than the concentrations encountered when cleaning syngas (160 g/m^3) by LePori and Soltes (1985).

Wang et al., 2006 conducted a study comparing methods for calculating cyclone pressure drops. In the study Wang conducted experiments to verify the TCD's method for calculating pressure drop across the cyclones with experimental data. A key finding from her work was that the recorded pressure drop for the test cyclones were approximately the same as those calculated using the TCD equations.

Hypothesis and Objectives

H_o: A single or series of properly designed cyclones can reduce the biochar concentrations by at least 90%.

H_a: The properly designed cyclone(s) do not reduce biochar concentrations by at least 90%.

The objectives of my research are:

1. Design and construct a testing system for determining cyclone's performances for varying concentrations of biochar.

2. Determine the biochar capture efficiencies and pressure drops of properly designed TAMU 1D2D and 1D3D cyclones used to separate biochar from gas resulting from the FBG of CGT.

3. Perform an economic analysis of the cost per kWh of the electricity produced by two methods: (a) direct feeding of the cleaned syngas into an internal combustion engine connected to a generator and (b) direct fueling of cleaned syngas into a boiler and subsequently to a steam turbine connected to a generator.

CHAPTER II

MATERIALS AND METHODS FOR EVALUATING CYCLONE PERFORMANCE

Introduction

The first step when evaluating PM abatement systems is to conduct a particle size distribution (PSD) on the PM that is being used for the testing. A significant quantity of biochar was obtained from previous FBG operations. Coulter Counter PSDs were performed on the biochar using the following procedure:

1. A sample of the biochar was sieved to remove particles larger than 100 micrometers (microns).
2. A small portion of the sieved biochar was placed in a beaker containing electrolyte and subjected to an ultrasonic bath to insure that aggregate particles were dispersed.
3. A minimum of 300,000 particles were sized for each PSD.
4. Figure 1 is a common PSD graph. Typically, PSDs are best defined by lognormal distributions defined by mass median diameters (MMDs) and geometric standard deviations (GSDs) (Cooper and Alley, 2011) The biochar used in this study had an MMD (AED) of 34 μm, and a GSD of 2.2.

Biochar produced from the TAMU FBG unit contains a large MMD when compared to common agricultural dusts such as cornstarch. Cornstarch has an MMD of 19 µm while the biochar has an MMD of 34 µm.

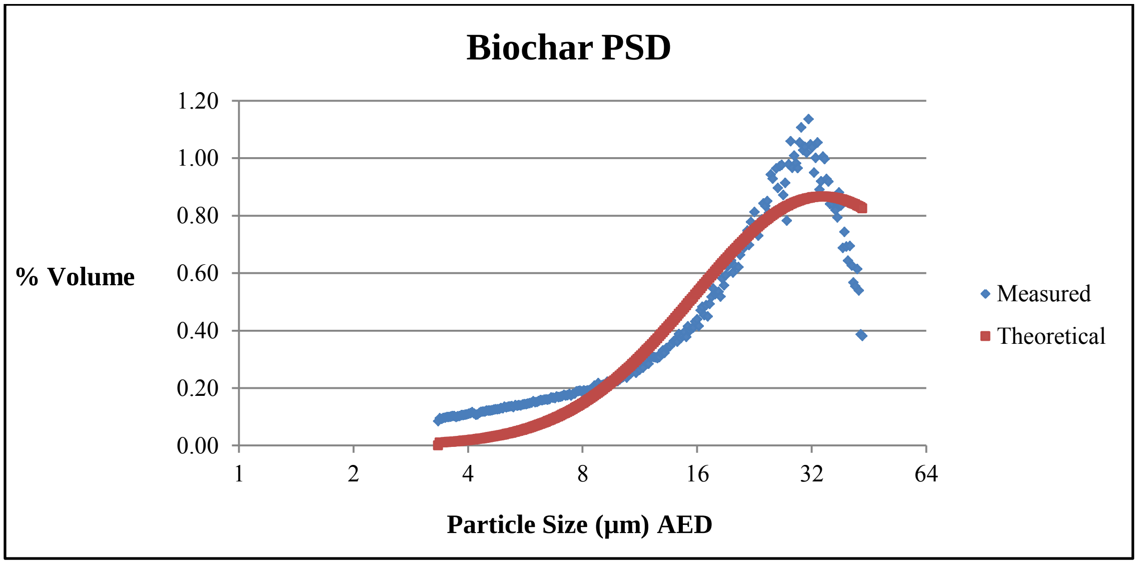

Figure 1. The particle size distribution of the biochar

Preliminary experimentation on the cyclone's capture efficiency of biochar was conducted. The performances of the cyclones in ambient air for loadings in the range of 200-400 g/min of biochar were evaluated. The test system was comprised of a 15.24 cm (6 in.) diameter 1D2D and 1D3D cyclone in series connection. A series of fans were used to pull air through the system to convey the biochar through the cyclones. A volumetric feeder was used to feed the biochar into the airstream. The major components of the test system are labeled in Figure 2.

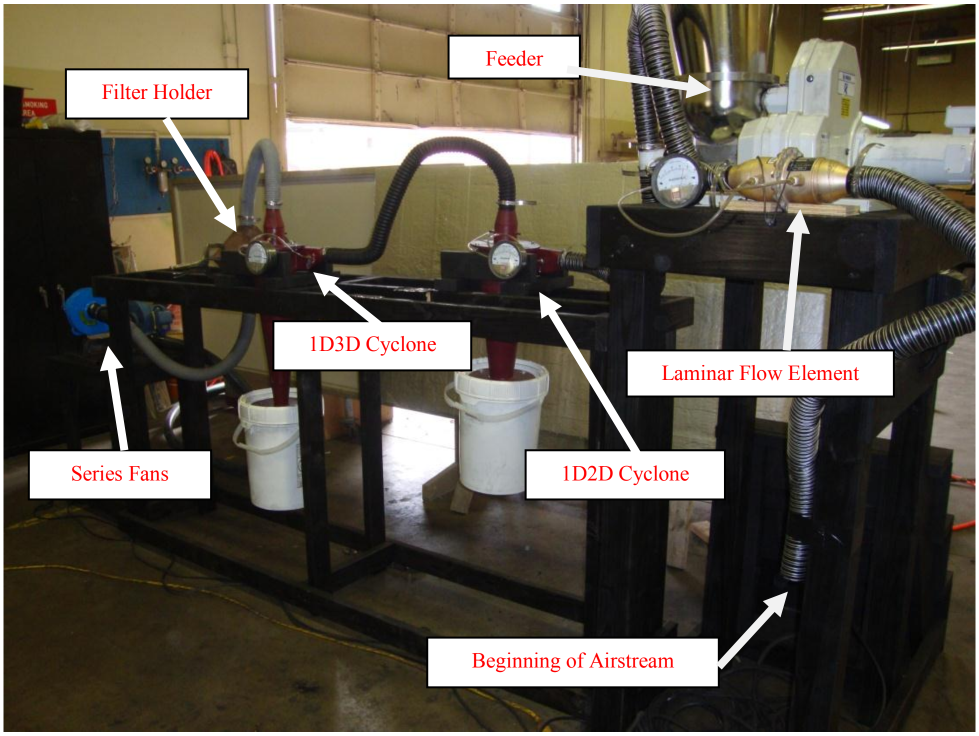

Figure 2. Initial cyclone performance screening experimental testing system.

The test concept was to capture the biochar with the cyclones and measure the mass of biochar penetrating the cyclones with a glass fiber filter. It was assumed that the filters would serve to accurately measure cyclone performances. However, the filters accumulated biochar at a much faster rate than was planned. After one to two minutes, very little air was penetrating the filter. Approximately 1.5 grams of biochar accumulated on the filter. This initial problem led to a revised method for determining cyclone capture efficiencies. The mass of biochar collected in the buckets below the cyclones were measured along with the mass of biochar fed for each test and during the tests. The ratios of these masses provide the measured efficiencies for each test. The char penetrated the cyclones was exhausted to the atmosphere.

Three replicates were conducted for the cyclones individually and in series. The mass of biochar was recorded that was put into the feeder. The duration of the test, the pressure drops across the cyclones, and the airflows through the system were also recorded. Efficiencies were calculated based upon the mass that passed through the cyclones. Capture efficiencies of 97% and higher resulted from testing the cyclones individually and in series. One of the significant findings from the initial testing was that the 1D2D cyclone captured a much larger fraction of biochar when it was placed first in a series connection with the 1D3D cyclone.

Methodology

In order to design the test conditions for the test system, estimates of the cyclone loading rates were simulated. The conditions that were simulated were those encountered from the operation of a TAMU FBG unit with a cross sectional area of 0.0929 m^2 ($1 ft^2$). Maglinao (2013) used Equivalence Ratios (ER), which are the ratios between the actual air to fuel ratio to the stoichiometric air to fuel ratio for operating the TAMU FBG unit with municipal solid waste. Normally, the gasification operation range is 20-40% of the stoichiometric air to fuel ratios. Using the range of ERs from 0.2-0.4, fuel to air ratios was assumed to be 0.6, 0.8, and 1.0 kg of CGT to 1 kg of air. Energy loading rates of the FBG unit ranged from 11,000-23,000 MJ/m^2-hr (1-2 $MMBtu/ft^2$-hr). The varying energy loading rates were obtained by varying the CGT feed rates (1, 1.6, 2.2 kg/min). Table 1 displays the fuel to air ratios, CGT feed rates, total gas flow, biochar production rates, and biochar concentrations at standard temperature and pressure (STP) for the 0.0929 m^2 area gasifier.

Table 1. Operating conditions for the 0.0929 m^2 mobile TAMU gasifier.

Fuel to Air Ratio	CGT Feed Rates	Gases Produced	Airflow at STP	Biochar Production	Biochar Concentrations
kg/kg	kg/min	kg	m^3/min	g/min	g/m^3
0.6	0.9	2.24	1.86	181	97.4
	1.4	3.36	2.79	272	97.4
	1.8	4.47	3.73	363	97.4
0.8	0.9	1.86	1.55	181	117
	1.4	2.79	2.32	272	117
	1.8	3.72	3.10	363	117
1	0.9	1.63	1.36	181	133
	1.4	2.45	2.04	272	133
	1.8	3.27	2.72	363	133

The biochar production rates and total gas flow at STP are the parameters that were simulated for evaluating the cyclone's performance. The 1D2D cyclone has a design inlet velocity of 732 ± 122 m/min (2,400 ± 400 fpm), while the 1D3D cyclone's design inlet velocity is 976 ± 122 m/min (3,200 ± 400 fpm). Total airflow through the cyclones were calculated by multiplying the inlet velocity by the inlet area of the cyclones. The cyclones that were used for the performance evaluations were 15.2 cm (6 in.) diameter 1D2D and 1D3D TCD cyclones. The 15.2 cm diameter cyclones have an inlet area of 0.0029 m^2 (0.0313 ft^2). When the inlet areas of the cyclone are multiplied by the design velocities, the results are the total airflow rates used for testing. Airflows calculated from the design inlet velocities at STP were the test conditions.

A randomized complete block statistical design with four replicates was used to evaluate the two factors and their interaction for both cyclones. The 1D2D testing is limited to two levels for the airflow due to the potentially low conveying velocity encountered at the bottom range of the design inlet velocity. The 1D3D contains three levels for the airflow factor. Both cyclones have the three aforementioned levels for biochar feed rate. Each test was replicated four times resulting in 24 tests for the 1D2D and 36 tests for the 1D3D cyclone. The testing parameters are illustrated in Table 2. Concentrations of biochar in g/m^3 were evaluated. The concentrations are calculated by multiplying the biochar feed rates by the airflow rates and are represented in Table 3. There were six levels of concentrations for the 1D2D cyclone and nine levels of concentration for the 1D3D cyclone. The range of simulated concentrations for the TAMU mobile gasifier (Table 1) was evaluated with the testing concentrations in Table 3.

Table 2. Randomized complete block experimental design with four replicates.

Cyclone	Factor	Level 1	Level 2	Level 3	Replicates
1D2D	Air Flow (m^3/min)	2.12	2.5	X	4
	Char Feed Rate (g/min)	180	270	360	
1D3D	Air Flow (m^3/min)	2.5	2.8	3.2	4
	Char Feed Rate (g/min)	180	270	360	

Table 3. Concentrations of biochar randomized complete block experiment design.

	Concentration Levels (g/m^3)									
Cyclone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Replicates**
1D2D	73	85	110	128	146	171	X	X	X	4
1D3D	57	64	73	85	96	110	114	128	146	4

The levels of concentrations were achieved using a controlled feed rate (rotary air lock). The biochar was fed into a system with controlled air flow rates using an automated positive displacement compressor. Pressure drops across the cyclones were recorded using digital differential pressure gauges. The airflow, temperature, barometric pressure, and pressure drops from the cyclone test were recorded utilizing Lab View Software. Efficiencies were calculated from the difference between the mass of biochar fed into the cyclones and the mass of biochar captured by the cyclones

Results and Discussion

The construction and calibration phase of the cyclone testing system was a trial and error process. Initially, an auger volumetric feeder was used. However, the feeder was affected by the vacuum created by the pneumatic conveying system. This feeder was replaced with one designed with the use of a rotary air lock powered by a variable speed DC motor. The biochar feed rates were 180, 270, and 360 g/min.

Figure 3 shows the internal mechanism of the airlock. The rotor contained eight steel paddles welded onto a shaft with rubber sheeting attached to the paddles. The hopper was designed to hold enough biochar to conduct tests of up to 20 minutes. An agitator was attached to the hopper to minimize bridging of the biochar.

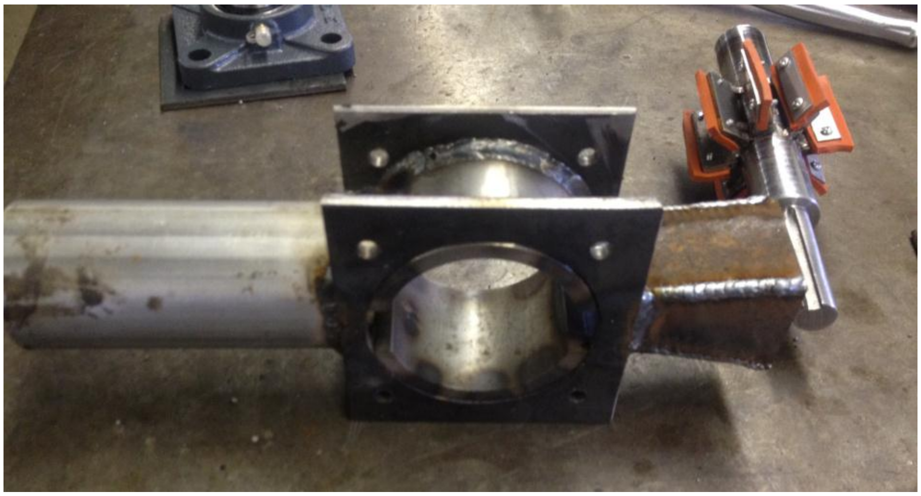

Figure 3. Internal mechanism of the rotary airlock.

A five horse power positive displacement compressor was the source of airflow for the test system. A laminar flow element (LFE) was used to monitor the flow rates. Equation 1 was the LFE equation that was programmed in LabView to regulate and monitor flow rates during testing. Pressure drop (ΔP) across the LFE and volumetric airflow has a linear relationship. Meriam, the manufacturer of the LFE, calibrates the LFE at the time of production. The linear relationship between ΔP and airflow was represented with airflow of 2.87 m^3/min and a ΔP of 1.99 kPa. The slope of 1.44 used in Equation 1 is derived from dividing the airflow by the ΔP. Equation 2 was used to calculate cyclone inlet velocities.

$$Q = 1.44 * \Delta P \qquad (1)$$

where
Q = volumetric airflow (m^3 min^{-1})
ΔP = pressure drop (kPa).

$$V_i = Q/A_i \qquad (2)$$

where
Vi = cyclone inlet velocity (m min^{-1})
Q = volumetric airflow (m^3 min^{-1})
A_i = inlet area of the cyclone (m^2).

Temperatures, relative humidity, pressure drops across the cyclones and LFE, along with the duration of the test were recorded with the data loggers integrated into the system. Data is recorded at two second intervals to allow for analysis. Figure 4 is the completed testing system. The system is constructed so that cyclones can be easily interchanged for performance evaluation.

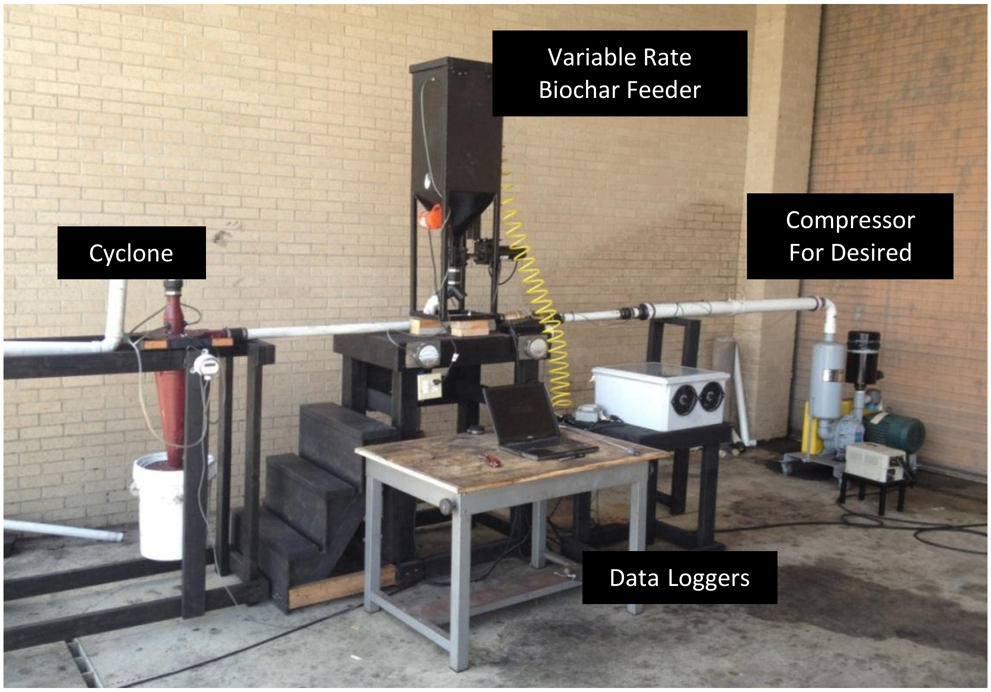

Figure 4. Improved cyclone performance test stand.

CHAPTER III

CYCLONE PERFORMANCE

Capture Efficiencies

Tests were conducted using the experimental design parameters to evaluate the cyclone's performance at ambient conditions. Cyclone efficiencies were calculated from the mass of biochar that penetrated the cyclones. Preliminary calibrations of the biochar feeder were performed. Inconsistencies were encountered in the feeding rates when the rotary airlock was set to specific speed. It was determined that the inconsistencies were a result of the varying bulk density of the biochar. A test was repeated when the biochar feed rate varied ± 10% of the desired feed rate. The following steps were followed for each test to calculate cyclone efficiency, with Equation 3 displaying the method used to calculate efficiency:

1. Measure and record the mass of biochar placed into the hopper (M_I).
2. Run a five minute long test.
3. Record the mass of biochar that remains in the hopper (M_R).
4. Record the mass of biochar captured by the cyclone (M_C)

$$CE = \frac{M_C}{M_I - M_R} * 100 \qquad (3)$$

where
CE = cyclone capture efficiency (%)
M_C = mass of biochar captured by the cyclone (grams)
M_I = mass of biochar placed in the hopper (grams)
M_R = mass of biochar remaining in the hopper (grams).

The 24 tests for the 1D2D and 36 tests for the 1D3D cyclone are displayed in Figure 5, ranked in order from lowest to highest efficiency. Table 4 is the initial statistical analysis performed on the data. The range, mean, standard deviation, and 95% confidence intervals were performed on the test results. Mean collection efficiency for the 1D2D cyclone was 96.6 ± 0.31% and 96.9 ± 0.22% for the 1D3D cyclone.

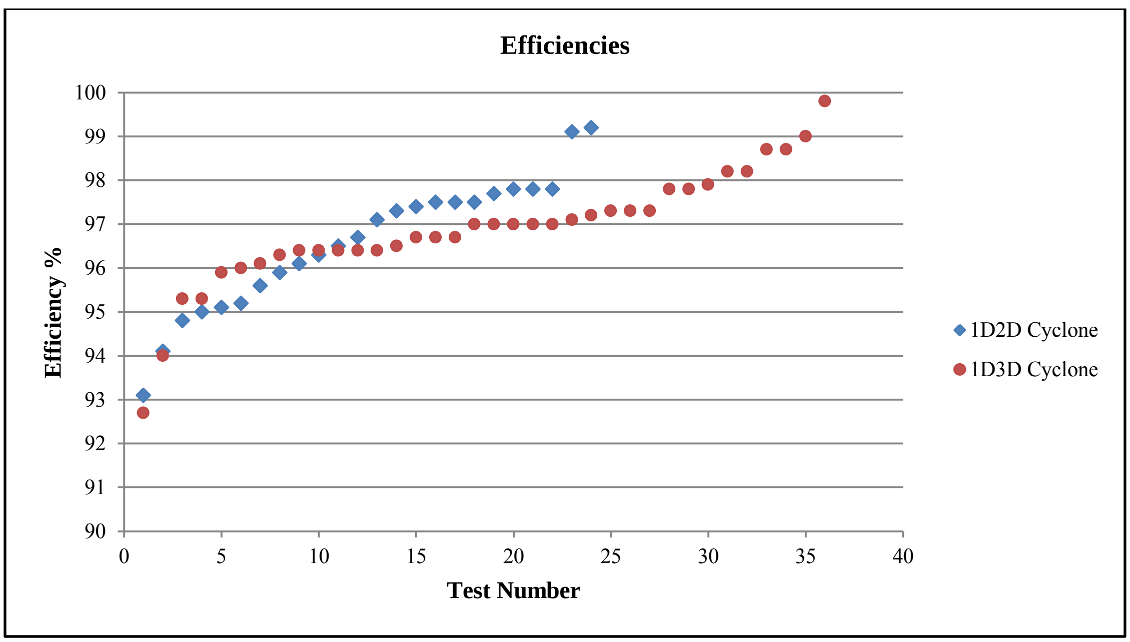

Figure 5. Ranked efficiencies for the 24 test of the 1D2D and the 36 tests for the 1D3D cyclone.

Table 4. Statistical analysis on the data collected from the experiment.

Cyclone	Number of Test	Range	Mean	95% C.I.
1D2D	24	93.1-99.2%	96.6 ± 0.31%	95.9, 97.2%
1D3D	36	92.7-99.8%	96.9 ± 0.22%	96.4-97.3%

An analysis of variance (ANOVA) was conducted on the randomized complete block experiment design to test for significance. The null hypothesis was that the levels of concentration do not have an impact on the collection efficiency; the alternative hypothesis was that the levels of concentration do have a significant impact on the collection efficiencies. The factor evaluated for the ANOVA was concentrations of biochar in g/m^3. The six levels of concentrations for the 1D2D and nine levels of concentration for the 1D3D are illustrated in Table 5 and Table 6. The ANOVA for both cyclones suggest the concentrations of biochar fed to the cyclones have a statistically significant impact on the cyclone's capture efficiency.

Table 5. The ANOVA to test for significance of the factors affecting the 1D2D cyclone's capture efficiencies.

Source	Sum of Squares	df	Mean Square	F-Value	p-value
A- Concentrations	25.33	5	5.07	3.20	0.0306*
Pure Error	28.50	5	1.58		
Cor. Total	53.83	23			

Table 6. The ANOVA to test for significance of the factors affecting the 1D3D cyclone's capture efficiencies.

Source	Sum of Squares	df	Mean Square	F-Value	p-value
A- Concentrations	32.12	8	4.01	3.16	0.0117*
Pure Error	34.28	27	1.27		
Cor. Total	66.40	35			

An analysis to determine the effects the concentration of biochar in g/m^3 had on capture efficiencies was conducted. All of the tests for the 1D2D and 1D3D are represented by the scatterplot in Figure 6. A linear regression was performed on the data with an R^2 value representing the linear correlation. The 1D2D cyclone has an R^2 of 0.261, while the 1D3D cyclone has an R^2 of 0.196. Weak linear correlation between the concentrations of biochar and capture efficiencies was present.

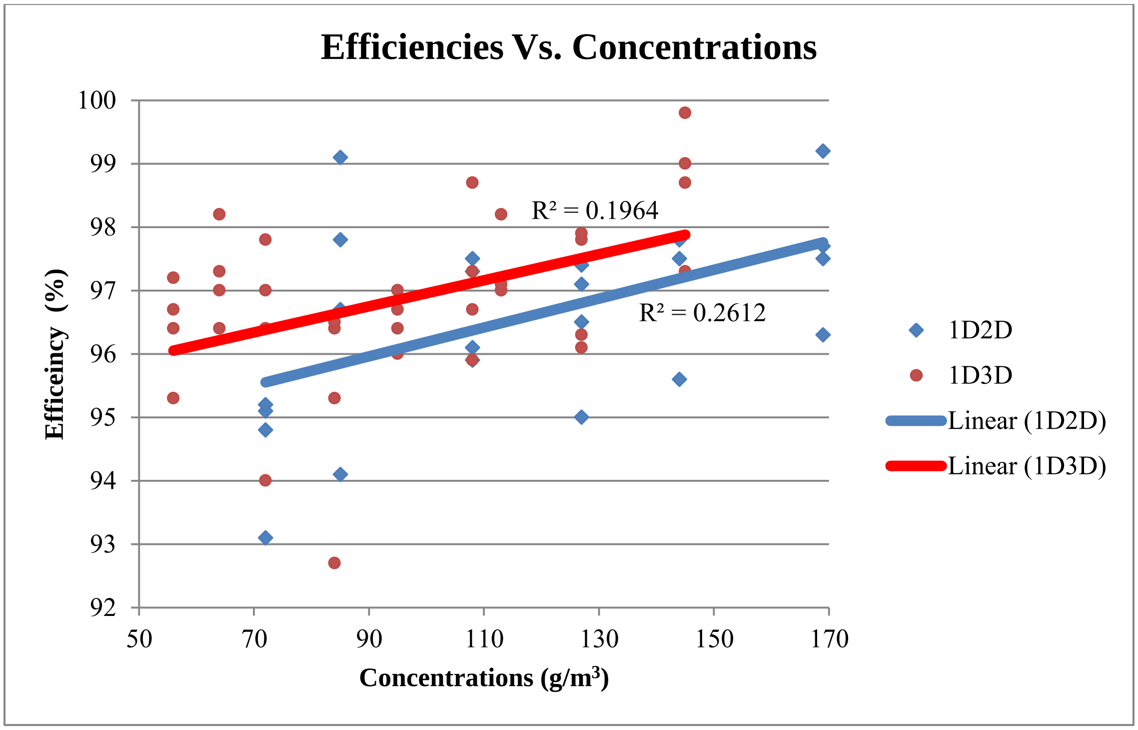

Figure 6. Collection efficiencies vs. concentrations of biochar. A linear regression was performed to determine if collection efficiency is affected by different levels of concentration of biochar.

A three period moving average was performed on all of the concentrations to smooth the data and eliminate outliers. Figure 7 and Figure 8 is the scatterplot of the data points with the moving average and linear regression for the 1D2D and 1D3D cyclone graphed. The 1D2D cyclone has an R^2 value of 0.739, and the 1D3D cyclone has an R^2 of 0.460. A strong linear correlation is not present from the moving average conducted on the data.

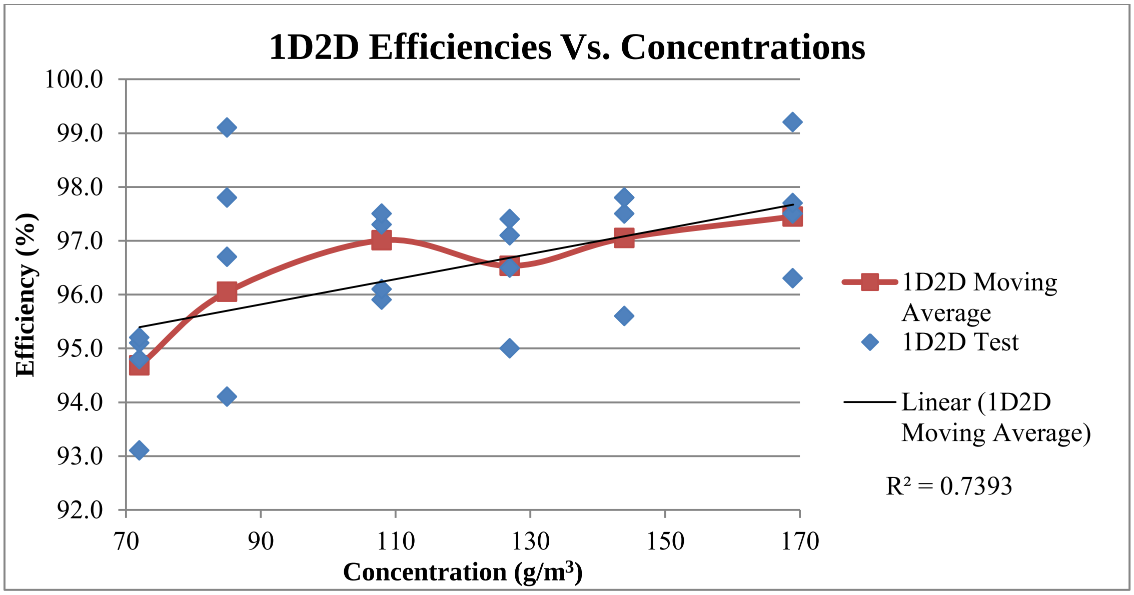

Figure 7. Moving average analysis on the concentrations of biochar vs. capture efficiencies for the 1D2D cyclone.

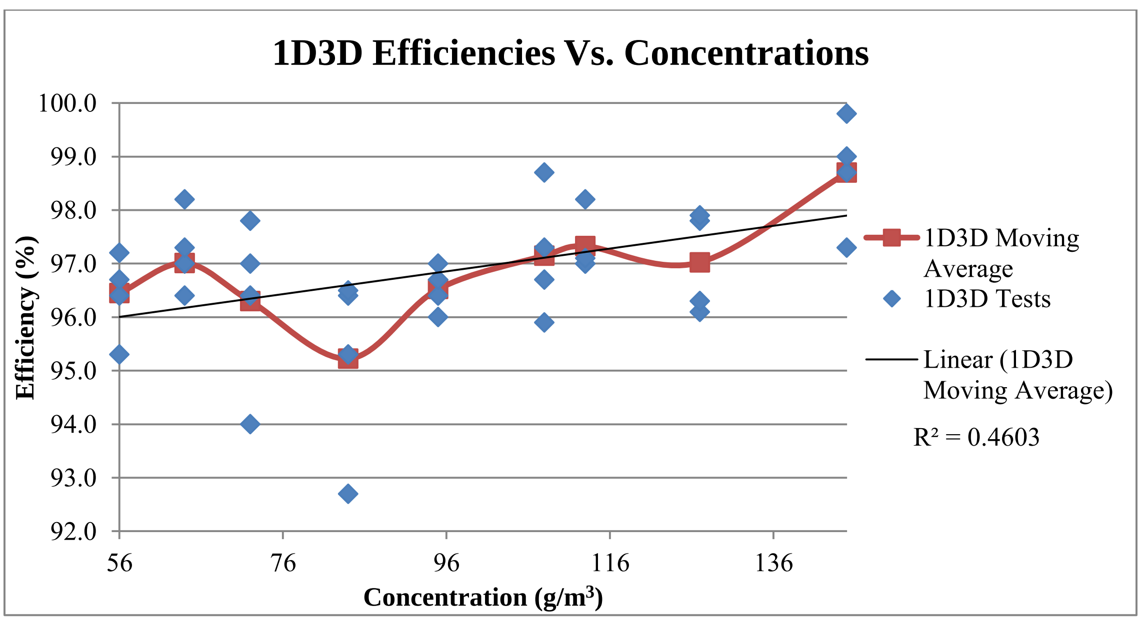

Figure 8. Moving average analysis on the concentrations of biochar vs. capture efficiencies for the 1D3D cyclone.

Pressure Drops

Pressure drops across the cyclones were recorded on two-second intervals during testing. The data were analyzed and averages were calculated for 20 seconds while the cyclones were conveying air only and 20 seconds while the cyclones were loaded with char. The inlet velocities of the cyclones remained the same for both data sets. The pressure drops between air only and air infused with biochar were different. On average, the pressure drop decreased by 74% for the 1D2D cyclone when loaded with biochar and 36% for the 1D3D cyclone. Figure 9 displays the difference in the pressure drops for the 1D2D cyclone and Figure 10 shows the difference for the 1D3D cyclone. The decrease in pressure drops were hypothesized to be a result of the biochar concentrations acting as a lubricant that reduced the friction between the airstreams and the inner walls of the cyclones.

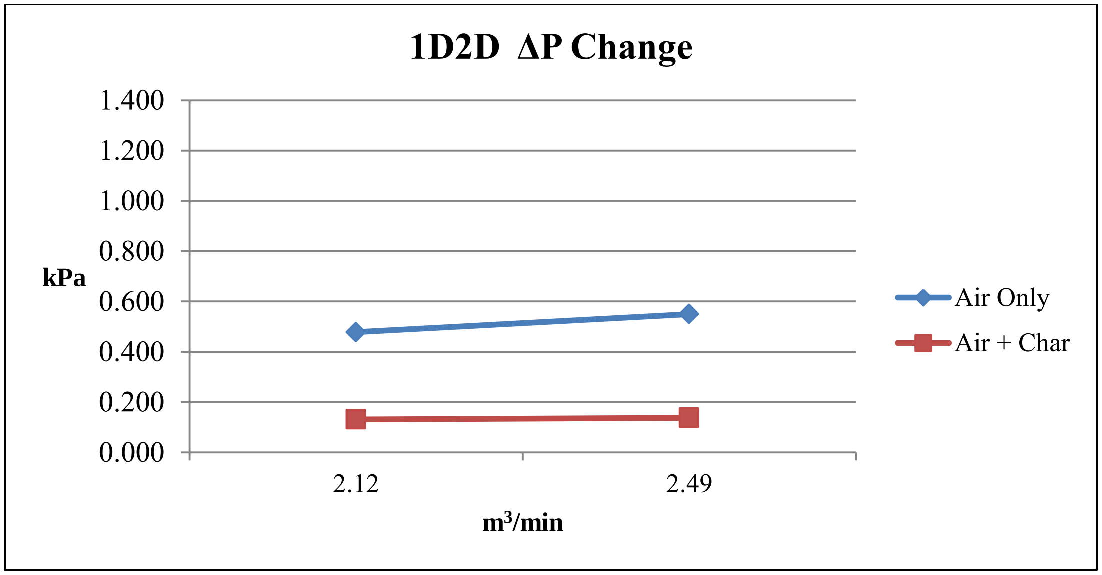

Figure 9. The difference between the average pressure drops across the 1D2D cyclone with air only and when the cyclone is loaded with biochar. The total average pressure drop is a decrease of 74%.

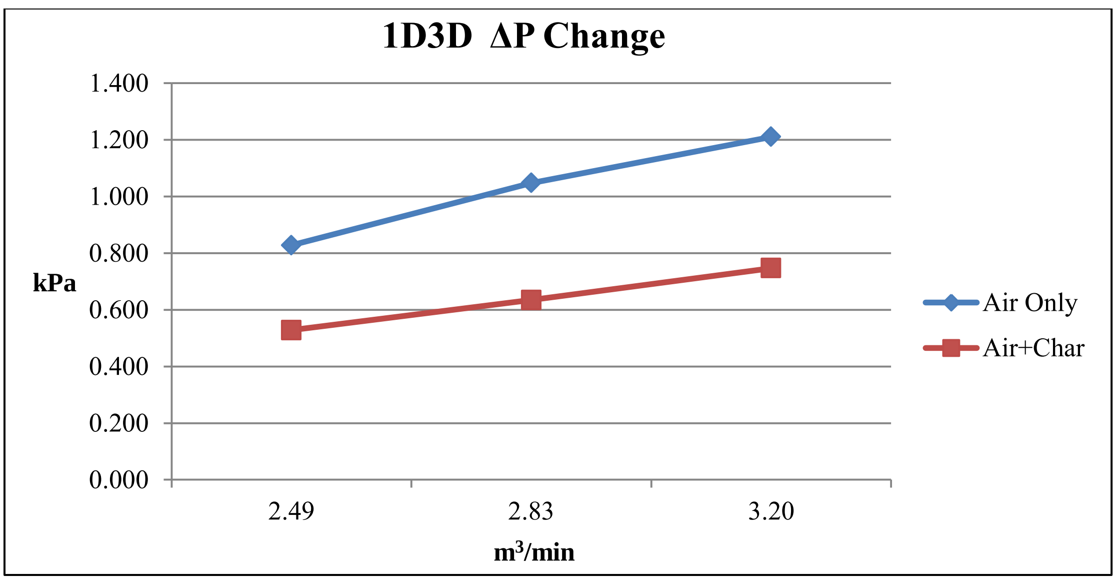

Figure 10. The difference between the average pressure drops across the 1D3D cyclone with air only and when the cyclone is loaded with biochar. The total average pressure drop is a decrease of 36%.

Data for the 1D2D and 1D3D cyclones were measured with a digital differential pressure gauge. The data is recorded on two-second intervals during the five minute test.

Airflow, temperature, and relative humidity are also recorded at the same intervals. Airflow, temperature, and relative humidity are used to calculate the pressure drops for the cyclones. The calculations use the cyclone's velocity pressure at the inlet and the outlet of the cyclones, along with the cyclone's respective K value, which is a constant for each of the TCD cyclones. Equation 4 is used to calculate air density from the recorded temperature, relative humidity, and barometric pressure. The barometric pressure gauge failed during the experimentations, and is assumed to be 1 atmosphere (atm) or 101.3 kilopascal (kPa). Molecular weight (M.W.) of the air is assumed to be 29 grams/mole. Table 7 lists the equations and constants for the outlet velocity of the cyclone (V_o), and the constants or K value for the 1D2D and 1D3D cyclones. Equation 5 was used to calculate the pressure drops for the TCD cyclones.

$$\rho_{air} = \frac{P_b * M.W.}{0.08206 * (t_{db} + 273)} \tag{4}$$

where
ρ_{air} = density of air (g L^{-1})
P_b = barometric pressure (atm)
t_{db} = dry bulb temperature (°C)

$$\Delta P = K * (VP_i + VP_o) \tag{5}$$

where
ΔP = cyclone pressure drop (kPa)
K = pressure drop constant (unit less)
VP_i = inlet velocity pressure of the cyclone (kPa)
VP_o = outlet velocity pressure of the cyclone (kPa)

Table 7. The equations to calculate the outlet velocity for the 1D2D and 1D3D cyclones along with the K values that are used in Equation 3 to calculate pressure drop across the cyclones.

Cyclone	Outlet Velocity	K Value
1D3D	$2\mathbf{V_i}/\pi$	5.1
1D2D	$1.28\mathbf{V_i}/\pi$	3.4

Table 8 is an example of the recorded data set along with the calculated pressure drops for the 1D2D cyclone using Equations 1, 2, 3, and the values from Table 7. Inlet velocity (V_i) is calculated by dividing the airflow in cubic meters per minute (m^3/min) by the inlet area of the cyclone in square meters (m^2).

Table 8. An example of the measured and calculated data. The main factors of focus include the recorded or actual cyclone pressure drop (ΔP) and the calculated or theoretical ΔP for the cyclones.

	Recorded Measurements				Calculated Measurements					
Obs.	**Temp.**	**R.H.**	**ΔP**	**Airflow**	$\mathbf{V_i}$	$\mathbf{V_o}$	$\boldsymbol{\rho_{air}}$	$\mathbf{VP_i}$	$\mathbf{VP_o}$	**Calculated ΔP**
	(C°)	(%)	(kPa)	(m^3/min)	(m/min)	(m/min)	(g/L)	(kPa)	(kPa)	(kPa)
1	28.8	70.8	0.3904	2.13	732	298	1.16	0.0862	0.0352	0.413
2	28.8	70.8	0.3904	2.11	727	296	1.16	0.0849	0.0346	0.406

A total of six tests for the 1D2D and nine tests for the 1D3D cyclone are analyzed. Three tests for the 1D2D cyclone are tests that were conducted at 2.12 m^3/min and the remaining three were tested at 2.5 m^3/min. Three tests for the 1D3D cyclone were conducted at 2.5 m^3/min, three at 2.8 m^3/min, and three at 3.2 m^3/min. Each test has 30 data points that sum to a one minute time interval. Averages and standard deviations are calculated from the 30 individual data points. Temperature and relative humidity vary for each test due to the experimentation being conducted outside and at different times of the day. The variations in air density are accounted for in the calculated pressure drop equations.

The null hypothesis tested was that the difference between the means is zero, or no significant difference, with an alternative hypothesis that the means have significant difference. The two means that are tested are the recorded means and the calculated means. Confidence intervals (C.I.) were calculated for both means. A t-distribution was used with the assumption that the means are from a normal distribution with an unknown population variance. Alpha (α) levels of .20, .10, .05, and .01 were used for the C.I. calculations. The lower limit of the C.I. (l) is represented in Equation 6 (Eq. 6) and the upper limit of the C.I. (u) is represented by Equation 7 (Eq. 7).

$$l = \bar{x} - t_{1-\frac{\alpha}{2},n-1} * s_{\bar{x}} \tag{6}$$

where
l = lower limit of confidence interval
$\bar{x}$ = sample mean
t = value from t-table
α = alpha
n = sample size
$s_{\bar{x}}$ = standard error of the sample

$$u = \bar{x} + t_{1-\frac{\alpha}{2},n-1} * s_{\bar{x}} \tag{7}$$

where

u = upper limit of confidence interval
$\bar{x}$ = sample mean
t = value from t-table
α = alpha
n = sample size
$s_{\bar{x}}$ = standard error of the sample

The null hypothesis of no significant difference is rejected if the two mean's C.I.s do not overlap. Test parameters for the interval testing are in Table 9. The parameters include the test number, cyclone used, airflow, and the recorded and calculated means and standard errors.

Results from the C.I. testing conclude that the differences between the recorded and calculated means are significantly different. The results from the four levels of α testing in Table 10 reject the null hypothesis that the difference between the means of recorded and calculated pressure drop are not significantly different.

Table 9. Parameters used for the C.I. testing of the ΔP for the cyclones.

Cyclone	Average Q (m^3/min)	Recorded Mean (kPa)	Recorded Standard Error	Calculated Mean (kPa)	Calculated Standard Error
1D2D	2.11	0.344	0.00154	0.406	0.00180
1D2D	2.13	0.299	0.00143	0.414	0.00148
1D2D	2.14	0.380	0.00089	0.416	0.00069
1D2D	2.48	0.341	0.00244	0.560	0.00215
1D2D	2.50	0.530	0.00110	0.566	0.00167
1D2D	2.54	0.512	0.00272	0.583	0.00388
1D3D	2.47	0.860	0.00478	0.96	0.00672
1D3D	2.47	0.833	0.00399	0.96	0.00350
1D3D	2.50	0.881	0.00155	0.98	0.00285
1D3D	2.78	1.032	0.01482	1.22	0.01383
1D3D	2.82	1.073	0.00349	1.26	0.00587
1D3D	2.86	1.049	0.00434	1.28	0.00673
1D3D	3.07	1.230	0.00944	1.49	0.01385
1D3D	3.17	1.204	0.00767	1.58	0.01275
1D3D	3.21	1.246	0.00246	1.62	0.00509

Table 10. The results from the hypothesis test that the difference in the means are not significantly different. All of the null hypotheses are rejected at the 80%, 90%, 95%, and 99% levels.

Cyclone	Average Q (m^3/min)	Recorded		Calculated		Recorded		Calculated		Recorded		Calculated		Recorded		Calculated	
		α=.20				α=.10				α=.05				α=.01			
		l	u	l	u	l	u	l	u	l	u	l	u	l	u	l	u
1D2D	2.11	0.342	0.346	0.404	0.409	0.341	0.346	0.403	0.409	0.340	0.347	0.403	0.410	0.340	0.347	0.402	0.411
1D2D	2.13	0.297	0.300	0.412	0.416	0.296	0.301	0.412	0.417	0.296	0.301	0.411	0.417	0.295	0.302	0.410	0.418
1D2D	2.14	0.379	0.381	0.415	0.417	0.378	0.382	0.415	0.418	0.378	0.382	0.415	0.418	0.378	0.382	0.415	0.418
1D2D	2.48	0.338	0.344	0.557	0.562	0.337	0.345	0.556	0.563	0.336	0.346	0.555	0.564	0.335	0.347	0.554	0.565
1D2D	2.50	0.528	0.531	0.564	0.568	0.528	0.532	0.563	0.569	0.528	0.532	0.563	0.570	0.527	0.533	0.562	0.570
1D2D	2.54	0.508	0.516	0.578	0.589	0.507	0.517	0.577	0.590	0.506	0.518	0.576	0.591	0.505	0.519	0.574	0.593
1D3D	2.47	0.854	0.867	0.949	0.967	0.852	0.869	0.947	0.969	0.851	0.870	0.944	0.972	0.849	0.872	0.942	0.975
1D3D	2.47	0.828	0.838	0.960	0.969	0.826	0.840	0.959	0.971	0.825	0.841	0.957	0.972	0.823	0.843	0.956	0.973
1D3D	2.50	0.879	0.883	0.975	0.982	0.879	0.884	0.974	0.983	0.878	0.884	0.973	0.984	0.878	0.885	0.972	0.986
1D3D	2.78	1.012	1.051	1.207	1.24	1.006	1.057	1.201	1.25	1.001	1.062	1.20	1.25	0.995	1.068	1.19	1.26
1D3D	2.82	1.068	1.077	1.25	1.27	1.067	1.079	1.25	1.27	1.065	1.080	1.247	1.271	1.064	1.081	1.25	1.27
1D3D	2.86	1.044	1.055	1.27	1.29	1.042	1.057	1.27	1.29	1.041	1.058	1.270	1.297	1.039	1.060	1.27	1.30
1D3D	3.07	1.217	1.24	1.47	1.51	1.21	1.25	1.47	1.52	1.21	1.25	1.46	1.52	1.21	1.25	1.46	1.53
1D3D	3.17	1.194	1.21	1.56	1.60	1.19	1.22	1.56	1.60	1.19	1.22	1.55	1.60	1.19	1.22	1.55	1.61
1D3D	3.21	1.243	1.25	1.61	1.63	1.24	1.25	1.61	1.63	1.24	1.25	1.61	1.63	1.24	1.25	1.61	1.63

The pressure drops for each cyclone was sorted from highest to lowest value for the recorded means. The means of both the measured and calculated pressure drops are plotted in comparison to inlet velocity. Figure 11 is the plotted means for the 1D2D cyclone and Figure 12 is for the 1D3D cyclone. Both charts display the recorded mean for the cyclones is lower than the calculated mean pressure drop. Variations were present for the 1D2D cyclone's recorded pressure drop. Theoretically, as the inlet velocity increases, so should the pressure drop across the cyclone. Several data points reveal that the recorded pressure drop decreases as the inlet velocity increases.

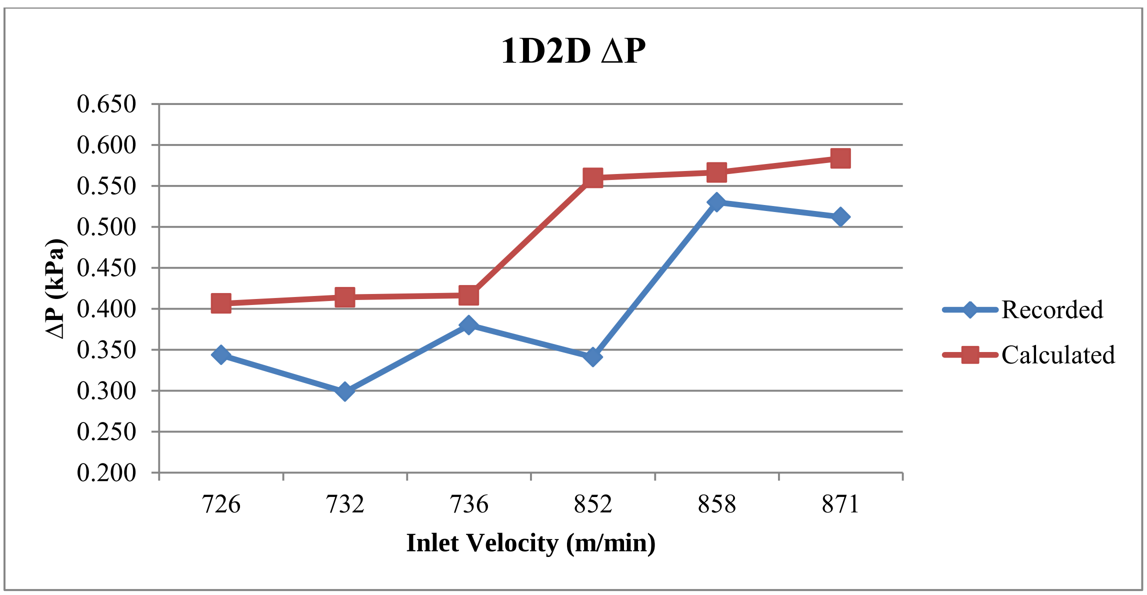

Figure 11. The plotted means of the calculated and recorded pressure drops for the 1D2D cyclone.

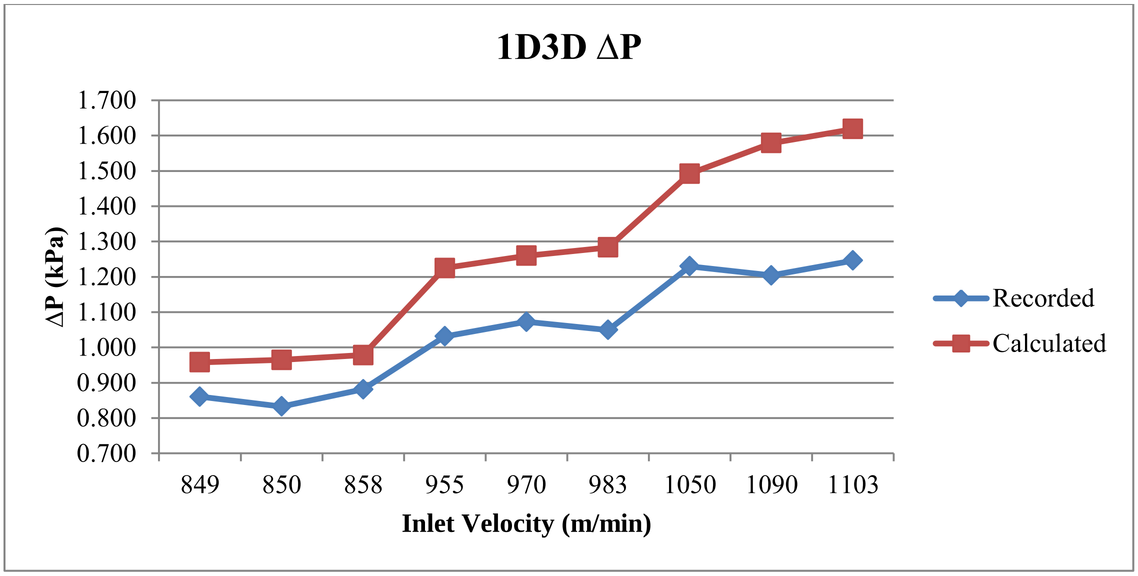

Figure 12. The plotted means of the calculated and recorded pressure drops for the 1D3D cyclone.

Conclusions

The biochar's PSD and MMD make it ideal for removal from an airstream with properly designed cyclones. It is vital that the biochar infused syngas is retained in an environment that is sealed with no exposure to oxygen. The high temperatures that are encountered at the exit of the gasifier pose as a potential explosion hazard if oxygen is introduced. Properly designed 1D2D and 1D3D cyclones can yield average biochar collection efficiencies of 96% and higher. Minimal correlation exists between concentrations of biochar and the capture efficiencies obtained. The ANOVA performed concludes that the biochar concentrations have a significant impact on the cyclone's performance. Higher efficiencies are obtained at the highest level of biochar concentration for both of the cyclones. There is no strong statistical evidence that correlation is present between the biochar concentrations and capture efficiencies.

Pressure drops across the cyclones decrease when concentrations of biochar are introduced to the cyclone. The 1D2D cyclone's pressure drop decreases by 74% and the 1D3D cyclone's pressure drop decreases by 36% when biochar is introduced. The analysis conducted on the pressure drops has indicated that there is a significant difference between the recorded and calculated pressure drops for both the 1D2D and 1D3D cyclones. Recorded pressure drops for both cyclones are lower than the calculated pressure drops.

The FBG unit does not need two cyclones for reducing biochar concentrations by 90% or higher. Both the 1D2D and 1D3D are capable of removing on average 97% of the concentrations of biochar in syngas. The 1D2D has a 74% decrease in pressure drop when concentrations of biochar are introduced to the cyclone. If the system designer were to use a single cyclone for syngas cleaning, the 1D2D cyclone would offer approximately the same average reduction in concentrations of biochar as the 1D3D, yet at a lower pressure drop. The lower pressure drops have the potential to reduce the power of the compressor that is used to fluidize the FBG unit. If the added pressure drop from a 1D2D and 1D3D cyclone in series is not an issue with the system's design, then it is recommended to use both cyclones for reducing concentrations. The series of cyclones will serve as a failsafe if one of the cyclones was to clog preventing heavy biochar loading to the engine or boiler.

CHAPTER IV

ECONOMIC FEASIBILITY OF THE GASIFICATION OF COTTON GIN TRASH

Introduction

Emsoff et al. (2006) demonstrated models and algorithms that determine optimal season length (L) in percent utilization (%U) as illustrated in Equation 8. This research was used to determine ginning costs in relation to ginning rate. Fuller et al. (1993) developed the %U model for cotton ginning where a cotton gin operating at 100%U would gin 1,000 hours per season and operate at 80% of its rated capacity (GR) to determine the number of bales ginned (BG) in a single season, as shown in Equation 9.

$$L = \frac{BG}{GR * 0.8} \quad (8)$$

where
L = season length (hours)
BG = bales ginned
GR = gin's rated capacity (%).

$$BG = GR * 0.8 * 1,000 * \%U \quad (9)$$

where
BG = bales ginned
GR = gin's rated capacity (%)
%U = percent utilization (%).

Cotton gin trash yield is dependent on the method used for harvesting cotton. The simulated cotton gin is located in the Lubbock, Texas area where the typical harvesting method is from the use of a stripper harvest with a cleaner that yields 181 kg (400 lbs.) of CGT per bale of ginned lint. Equations 10 and 11 were used to calculate the total amount of CGT produced by using the previously mentioned parameters. Table 11 is used to compare the varying cotton gin sizes, their %U for the season, and the amount of CGT produced each season.

$$\frac{40\text{bales}}{\text{hr}} \times \frac{1{,}000\text{ hrs}}{\text{season}} \times 200\%\text{U} \times 80\%\text{ Eff.} = 64{,}000\text{ bales} \tag{10}$$

$$\frac{64{,}000\text{ bales}}{\text{season}} \times \frac{181\text{ kg CGT}}{\text{bale}} \times \frac{1\text{ tonne}}{1{,}000\text{ kg}} = 11{,}600\text{ tonnes CGT} \tag{11}$$

Table 11. CGT production based on utilization rates

Gin Rating (bph)	Utilization (%)	Bales/Year	CGT (tonnes/yr)	Operation (hrs)
20	100	16,000	2,903	1,000
20	200	32,000	5,805	2,000
40	100	32,000	5,805	1,000
40	200	64,000	11,600	2,000
60	100	48,000	8,708	1,000
60	200	96,000	17,400	2,000

It was determined that a FBG unit used to fuel an internal combustion engine combined heat and power plant (ICPP) would require $1 million per MW of power, as opposed to $2 million per MW of power when using the FBG unit to fuel a boiler and steam turbine combined heat and power plant (SPP) (Calvin B. Parnell, Jr., TAMU Regents Professor, personal communication, 13 February 2013). The use of cyclones to remove biochar particles from the syngas will enable a FBG unit to directly fuel the ICPP. Direct fueling of the syngas to the ICPP will lower capital investments for energy generation. Power requirements for cotton gins were determined from a more conservative energy usage of 50 kWh/bale, rather than the average power consumption per bale from the TCGA of 43 kWh/bale. The conservative approach is to account for fluctuations in the power requirements of the cotton gin. A 20 bph rated facility would require a FBG power plant that produces 1 MW of electricity, compared to a 2 MW facility for a 40 bph gin and a 3 MW facility for a 60 bph rated cotton gin.

Methodology

The economic analysis performed was simulating a 40 bph cotton gin located in the Southern High Plains of Texas where cotton harvesting methods produce approximately 181 kg (400 lbs.) of CGT per bale of ginned lint. The gin has a utilization factor of 200%, which leads to a season lasting 2,000 hours. A five-year survey from the Texas Cotton Ginners association from 2007-2011 reports that cotton gins in Texas have an average energy consumption of 43 kWh of electricity per bale and 4.50 m^3 (0.159

MCF) of natural gas per bale of ginned lint (TCGA, 2013). Information from the United States Energy Information Administration (EIA) was used to predict future prices of electricity and natural gas for industrial consumers. Crystal Ball modeling software was used to fit the distributions and predict prices for twenty years from the historical data with the use of a predictor tool within the software (Oracle, 2012). Total electricity consumed for the 64,000 bales produced is 2,750 MWh and 288,000 m^3 (10,170 MCF) of natural gas, and is assumed to remain constant for the twenty years of the simulation. Table 12 is the predicted prices and total energy costs used for the twenty year period.

The average U.S. inflation rate for 2012 of 2.1% (Coin News, 2013) was used in the calculations. A loan was used to cover all capital costs with an interest rate of 3.25% and no down payment for a period of twenty years. The loan amortization schedule was computed. Yearly loan payments for the 2 MW ICPP are $138,000; while the 2MW SPP's annual payments are $275,000. Purchased equipment was depreciated using the United States Internal Revenue Service's (IRS) Modified Accelerated Cost Recovery System (MARCS) with the depreciation based on a Declining Balance (DB) method (Wright, et al 2012). The power plants have a seven year depreciation period with the 200% DB depreciation method and no salvage value is used.

Table 12. Predicted prices for electricity and natural gas.

Year	Electricity Price	Total Electricity Expenses	Natural Gas Price	Natural Gas Price	Total Natural Gas Expenses
	$/kWh		$/m^3	$/MCF	
2012	$0.09	$238,000	$0.17	$4.81	$48,600
2013	$0.09	$242,000	$0.17	$4.81	$49,300
2014	$0.09	$247,000	$0.17	$4.81	$49,400
2015	$0.09	$251,000	$0.18	$5.10	$50,400
2016	$0.09	$256,000	$0.18	$5.10	$51,200
2017	$0.09	$261,000	$0.18	$5.10	$51,500
2018	$0.10	$265,000	$0.18	$5.10	$52,000
2019	$0.10	$270,000	$0.18	$5.10	$52,700
2020	$0.10	$275,000	$0.19	$5.38	$54,600
2021	$0.10	$279,000	$0.20	$5.66	$56,600
2022	$0.10	$284,000	$0.20	$5.66	$58,300
2023	$0.10	$288,000	$0.21	$5.95	$60,300
2024	$0.11	$293,000	$0.22	$6.23	$62,600
2025	$0.11	$298,000	$0.22	$6.23	$64,600
2026	$0.11	$302,000	$0.23	$6.51	$65,900
2027	$0.11	$307,000	$0.23	$6.51	$67,400
2028	$0.11	$312,000	$0.24	$6.80	$68,200
2029	$0.11	$316,000	$0.24	$6.80	$68,600
2030	$0.12	$321,000	$0.24	$6.80	$69,100
2031	$0.12	$325,000	$0.24	$6.80	$70,200

The labor costs are based upon the amount of people that are required to operate the Mobile TAMU FBG plant. The mobile gasifier required one mechanic, one operator, and two general laborers or student workers to have the gasifier fully functional. Average annual salaries were gathered from Salary.com (2013). The average annual US salaries were increased by 20% due to the long periods of work encountered during ginning season (90 day period). The annual salaries and total labor expenses per year are represented in Table 13, with the labor expenses totaling to $416,000 per year and were used for the base operating expenses for the analysis.

Table 13. Average salaries and total annual salaries paid for each year.

Position	Annual Salary	Number Per Shift	Cost Per Shift	Total Cost Per Year
Operator	$50,000	1	$50,000	$150,000
Mechanic	$62,000	*	*	$62,000
Laborer	$34,000	2	$68,000	$204,000
			Total=	$416,000

*Mechanic works 1 shift each day and is on call 24/7 during ginning season

Three shifts were created for the power plant to operate for 24 hours a day, seven days a week for the ginning season. The three shifts were separated into eight hour work days. Each shift contains one operator and two laborers. The mechanic works only one eight hour shift per day, yet remains on call if a mechanical failure occurs. Ginning season consumes approximately 7,550 tonnes (8,320 tons) of CGT. The remaining 4,063 tonnes (4,480 tons) of CGT that is available from the ginning season enables the power plant to operate for an extra 2,560 hours beyond the ginning season. Table 14 displays the amount of CGT that is produced each season for the simulated cotton gin, the energy consumed by the cotton gin, and the extra electricity available for sale.

Table 14. The amount of CGT produced, total energy produced, consumed, and available for sale after each ginning season.

Total CGT	Total Energy Available	Electricity Consumed	Extra Electricity	Extra Electricity Operating Hours
tonnes	MWh	MWh	MWh	hours
11,600	7,880	2,760	5,120	2,560

The remaining operating hours for the power plant are approximately 2,560 hours per year upon completion of the cotton ginning season. If the power plant were to operate for sixteen hours each day for seven days a week, it would operate for an additional 160 hours in addition to the ginning season. Table 15 shows the total amount of hours that the employees work. The sixteen hour work days are separated into two eight hour shifts. The three shifts are separated into shifts A, B, and C. Each shift will work eight days on and four days off, rotating between shift times. Table 16 is a twelve week work schedule for the employees. Each employee over the twelve week work period will work on average of 40 hours each week. The mechanic will be required to work at least 40 hours a week and will also be on call when equipment fails. A total of 40 weeks were spent working for the employees with a potential twelve week vacation to reward them for their efforts during the demanding ginning season. The additional four weeks added to the total operating weeks in Table 15 are to account for the power plant not operating at all times. This scenario also incorporates additional maintenance costs of 3% of the total investment (Craig and Mann, 1996), along with the addition of 2% of the total investment costs for taxes and insurance.

Table 15. Power plant operating hours for the two operating seasons.

Season	Energy Operating Hours	Operating Days	Operating Weeks	Plant Hours/Day	Days/Week	Shifts/Day	Hours/Shift	Total Hours/Employee
	hours	days	weeks	hours	days	shifts	hours	hours
Ginning	2,000	90	13	24	7	3	8	720
Energy Sales	2,560	189	27	16	7	2	8	1,080
Totals	4,560	279	40	-	-	-	-	1,800

Table 16. Employee work schedule.

Weeks 1-4

Shift	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
S1	A	A	A	A	C	C	C
S2	B	B	B	B	B	B	B
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	C	C	C	C	C	B	B
S2	B	A	A	A	A	A	A
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	B	B	B	B	B	B	A
S2	A	A	C	C	C	C	C
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	A	A	A	A	A	A	A
S2	C	C	C	B	B	B	B

Weeks 5-8

Shift	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
S1	C	C	C	C	C	C	C
S2	B	B	B	B	A	A	A
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	C	B	B	B	B	B	B
S2	A	A	A	A	A	C	C
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	B	B	A	A	A	A	A
S2	C	C	C	C	C	C	B
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	A	A	A	C	C	C	C
S2	B	B	B	B	B	B	B

Weeks 9-12

Shift	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
S1	C	C	C	C	B	B	B
S2	A	A	A	A	A	A	A
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	B	B	B	B	B	A	A
S2	A	C	C	C	C	C	C
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	A	A	A	A	A	A	C
S2	C	C	B	B	B	B	B
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
S1	C	C	C	C	C	C	C
S2	B	B	B	A	A	A	A

Dornburg and Faaij (2001) estimated that the annual operating costs including maintenance, insurance, and personnel for different renewable energy power plants varies 3-6% of the total investment costs. The operating expenses were varied from 6, 12, and 18% of the total investment costs in one scenario. The varying operating expenses are compared to the base cost estimates to account for uncertainty in the operating expenses.

Results and Discussion

The FBG power plants are operating with an overall energy conversion factor of 15%, which is applied to the calculations for the ICPP and SPP. The simulated cotton gin requires 1.38 MWh/hr to satisfy the electricity demands, along with 5,370 MJ/hr (5.088 MMBtu/hr) of heating energy for drying the cotton. Approximately 85% of the CGT's energy is lost in the form of waste heat. The FBG unit will consume 2.032 tonnes (2.24 tons) of CGT each hour, or 33,080 MJ/hr (31.4 MMBtu/hr) of energy to produce the desired amount of electricity. The combined heat and power plant (CHP) only requires 16.2% of the 33,080 MJ/hr waste heat energy to be captured by an air-to-air heat exchanger for drying the cotton.

Revenue costs were comprised of the savings from not purchasing electricity and gas for the duration of the ginning season, the selling of biochar at $22.05/tonne ($20/ton), and the selling of extra electricity back to the utility company. The biochar selling price is varied from the base price of $22.05/tonne to $11.02/tonne ($10/ton) and

$33.07/tonne ($30/ton). An excess of 4,063 tonnes (4,480 tons) of CGT is available after the energy requirements have been fulfilled for the ginning season. The extra CGT enables the power plant to serve as an electricity provider. A net metering system with the local utility provider is assumed to be used for the power plant. The net metering system will allow the small biomass power plant to sell excess electricity back to the utility provider at the wholesale price, and was used as the base case for the evaluation. The sell back prices were varied by 10, 50, and 90% of the wholesale price to account for the uncertainty in the sell back value of the electricity. Government subsidies or renewable-energy tax credits were not used in this evaluation. Operating costs (labor, taxes, insurance, and maintenance) are used as expenses. Base net returns with five-year intervals for the ICPP are represented in Table 17 and Table 18 for the SPP.

Table 17. Base net returns for the ICPP.

	Revenue -	**Expenses =**	**Net Returns**
Year	**Energy Savings and Electricity and Biochar Sales**	**Yearly Expenses**	**Annual Net Returns**
2012	$780,000.00	$516,000.00	$264,000.00
2016	$835,000.00	$561,000.00	$274,000.00
2021	$907,000.00	$622,000.00	$285,000.00
2026	$982,000.00	$690,000.00	$292,000.00
2031	$1,050,000.00	$766,000.00	$284,000.00

Table 18. Base net returns for the SPP.

	Revenue -	Expenses =	Net Returns
Year	**Energy Savings and Electricity and Biochar Sales**	**Yearly Expenses**	**Annual Net Returns**
2012	$780,000.00	$616,000.00	$164,000.00
2016	$835,000.00	$669,000.00	$166,000.00
2021	$907,000.00	$743,000.00	$164,000.00
2026	$982,000.00	$824,000.00	$158,000.00
2031	$1,050,000.00	$914,000.00	$136,000.00

A statement of cash flows was created to produce net cash flows after debt. A marginal tax rate of 41% is assumed on all income because the revenue generated from extra electricity and biochar sales are at the highest tax bracket. After tax net returns and tax savings from depreciation and interest were also included in the cash flow statement. The result of the cash flow statement was an annual net cash flow after debt. Figure 13 compares the annual net cash flow after debt for the ICPP and SPP. Year 1 represents 2012, while year 20 represents the year 2031. Net cash flows are high for the first seven years. This trend is due to the depreciation for both plants lasting only seven years. The ICPP does have higher net cash flows for every year besides the first year for the base cases. The net present value (NPV) using the base assumptions for the ICPP were $1,480,000, while the NPV for the SPP was -$160,000.

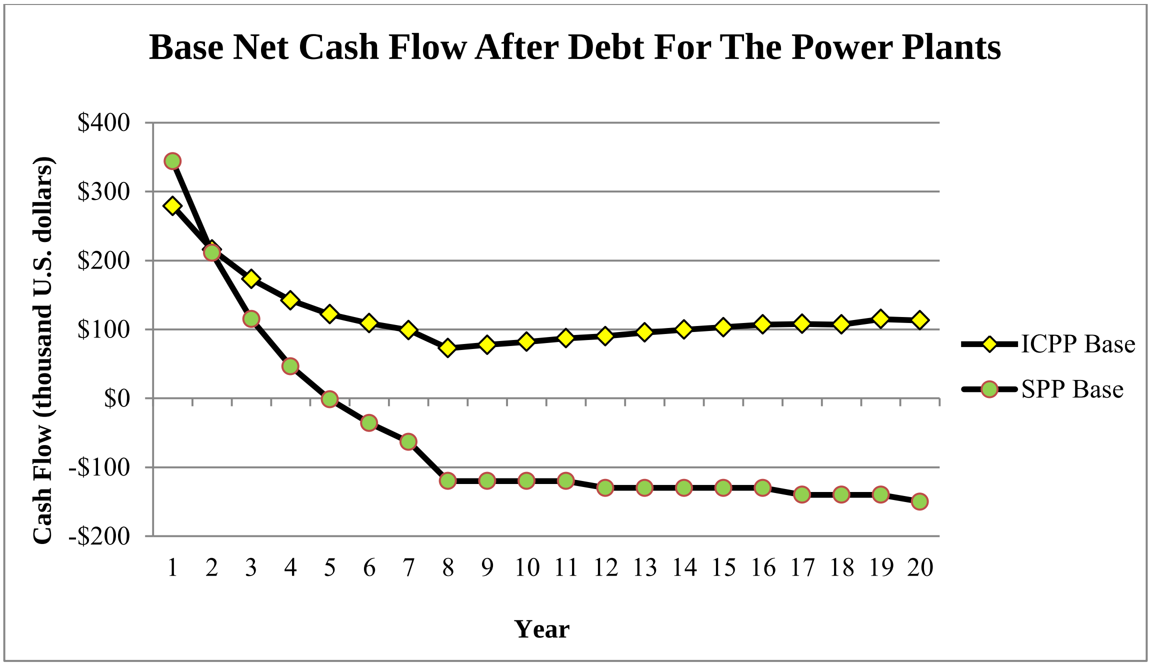

Figure 13. Net annual cash flows after debt for the ICPP.

A sensitivity analysis was performed to account for uncertainty with the assumptions that were made. The biochar and electricity selling prices were varied, along with the method of calculating operating costs. The variations to the parameters are compared to the base calculations for both power plants. The results from the sensitivity analysis are represented in Table 19. The table includes the base NPV for the power plants, along with the NPV's of the cash flows after debt for both power plants. The NPVs are most sensitive to the varying selling price of the electricity for both power plants. The operating expenses also have a large impact on the NPVs for the power plants. Biochar selling price has the least amount of change for the NPVs.

Table 19. Sensitivity analysis on the NPV of the net cash flows after debt for the power plants.

Parameter	ICPP	Change	SPP	Change
Biochar				
Base	$1,480,000	-	-$160,000	-
$10	$1,280,000	-10%	-$370,000	-131%
$30	$1,670,000	13%	$20,900	113%
Electricity				
Base	$1,480,000	-	-$160,000	-
10%	-$2,100,000	-240%	-$3,800,000	-2300%
50%	-$520,000	-135%	-$2,200,000	-1300%
90%	$1,080,000	27%	-$570,000	-260%
Expenses				
Base	$1,480,000	-	-$160,000	-
6%	$5,170,000	249%	$3,340,000	2190%
12%	$4,050,000	174%	$1,100,000	788%
18%	$2,930,000	98%	-$1,100,000	-590%

A second evaluation of the economic model was conducted. If a cotton gin was no longer able to purchase electricity and natural gas from a utility provider, the cotton gin would need to provide its own source of energy for operation. The cost to produce the electricity is evaluated based upon the cost per kWh of electricity required. Net cash flows are comprised of all of the expenses incurred for operating the power plants. Revenues are not included in the total cash flow statement, only expenses. The expenses are comprised of operating costs and the annual loan payment. Tax savings from depreciation and interest incurred from the loan amortization schedule are the only positive values for the annual cash flow statements. The net cash flows after debt are divided by the total energy requirements for the ginning season. The cost to produce electricity per kWh for both of the power plants is represented by Figure 14. The cost to produce electricity for both power plants is compared to the projected industrial cost to purchase electricity for the twenty year period. The cost to produce electricity is higher than the predicted purchase price of electricity for all of the simulated time periods except for the first year. The low cost to produce electricity was due to the tax savings from depreciation for the first year. The average predicted price of electricity is \$0.10/kWh, while the average price to produce electricity for the ICPP is \$0.20/kWh and \$0.26/kWh for the SPP.

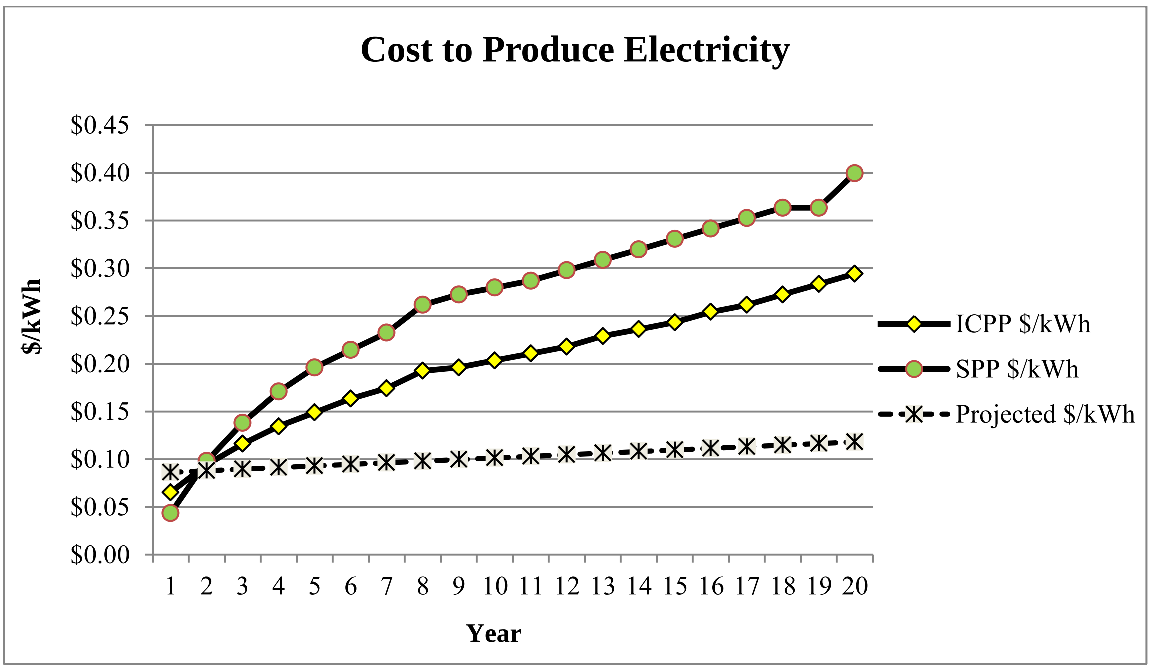

Figure 14. Cost to produce electricity per kWh for the power plants.

Conclusions

Economic feasibility of renewable energy systems are an important consideration prior to implementation. The fueling of a power plant with syngas produced from the

FBG of CGT has vast differences in feasibility based on capital costs. The ICPP has initial capital costs that are half of the capital costs for a SPP. The sell back price of extra electricity produced has the largest percent change in the NPV's for both power plants from their base calculations. The operating costs variations have the second largest impact on the NPVs, followed by the biochar selling price which had the least amount of effect on the NPVs. The price to produce electricity for the power plants was evaluated in a scenario where the cotton gin would not be able to purchase electricity from a provider, or the price to purchase electricity increases significantly. The average price to produce electricity over the twenty year period for the ICPP is \$0.20/kWh, and \$0.26/kWh for the SPP.

The parameter estimations are contingent upon the FBG unit successfully producing the amount of syngas that is required to fuel the power plants. The TAMU FBG unit has not been scaled to the simulated sizes of having a potential output of 2 MW of power. The ICCP needs to be further evaluated to determine the wear that the penetrating concentrations of biochar have on the engine. A scale model is recommended to be evaluated to determine the long term effects that the biochar concentrations have on the engine.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Cotton gins produce a large amount of CGT as a by-product of cotton ginning each year. FBG of CGT has the potential for a cotton gin to become energy independent and an electricity producer. Direct fueling of syngas to an internal combustion engine powering a generator is estimated to have half the capital costs of a FBG unit fueling a steam boiler and turbine for electricity production. Biochar must be removed from the syngas prior to direct fueling of the engine. Cyclones were used to remove the concentrations of biochar from the syngas stream. A laboratory scale test system was constructed to evaluate the cyclone's performance for removing biochar from standard temperature and pressure air. An economic feasibility study was conducted for a FBG unit fueling an internal combustion engine power plant and a steam boiler and turbine power plant.

Objective 1

The PSD of the biochar has an MMD (AED) of 34 µm, and a GSD of 2.2. In comparison to common agricultural dusts such as cornstarch (MMD (AED) 19 µm), biochar is much larger. Preliminary experiments were conducted using a volumetric biochar feeder and a 1D2D and 1D3D cyclone in series. The feeder was unable to accurately dose the biochar into the airstream. A majority of the biochar was captured by the first cyclone in the series which was the 1D2D cyclone.

Tests parameters were developed from a range of operating conditions for the TAMU mobile FBG unit with a cross sectional area of 0.0929 m^2 (1 ft^2). The concentrations of biochar that were produced from feeding the gasifier 0.9, 1.4, and 1.8 kg/min of CGT range from 97.4-133 g/m^3. A randomized complete block experiment with four replicates was designed to include and expand the range of biochar concentrations that enter the 1D2D and 1D3D cyclone. A new test system was constructed that incorporates a digitally controlled positive displacement compressor and digital magnahelic gauges. A rotary airlock was designed and constructed to accurately feed biochar into the airstream at the desired rates.

Objective 2

A total of 24 and 36 tests at ambient conditions were conducted on the 1D2D and 1D3D cyclones. Biochar capture efficiencies were calculated by recording the mass of biochar that fed to the cyclones, and then measuring the amount of mass that was captured by the cyclones. Each test had a duration of five minutes, with relative humidity, temperature, and pressure drops across the cyclones being recorded on two second intervals. The mean collection efficiency of the 1D2D cyclone was 96.6 ± 0.31% and 96.9 ± 0.22% for the 1D3D cyclone. An ANOVA was conducted to determine the effects that the test variable, concentrations of biochar, had on the collection efficiencies of the cyclones. Concentrations for both the 1D2D and 1D3D cyclone have a significant impact on the cyclone's collection efficiency. A three period moving average was performed on the collection efficiencies for the cyclones. A linear regression was performed on the moving average analysis to determine correlation between collection efficiencies and concentrations of biochar. The results from the analysis were that there was no statistically significant correlation between collection efficiencies and biochar concentrations. The highest collection efficiencies were obtained for both cyclones at the highest level of concentrations of biochar.

Data collected for the pressure drops across the cyclones was analyzed. The first test performed was determining the difference in pressure drops for the cyclone when air only and air infused biochar was conveyed through the cyclone at the same inlet velocities. A 20 second average was used from each of the tests at the same inlet velocities for both cyclones. The averages for air only and air infused with biochar were analyzed. The pressure drops across the 1D2D cyclone is 74% lower with biochar introduced into the airstream than with air only, and a 36% decrease in pressure drop for the 1D3D cyclone. The second test conducted on the cyclone's pressure drop data was to determine the significance of the difference between the recorded pressure drops across the cyclones and the calculated pressure drops using the TCD method. A t-test was conducted with alpha levels of .20, .10, .05, and .01. All of the recorded pressure drops are significantly different than the calculated pressure drops using the TCD method. Further analysis is needed to determine if changes to the TCD method's equations are needed.

Objective 3

A 40 bph cotton gin was simulated operating at 200%U (2,000 hrs/season), and located in the Lubbock, Texas region, handling stripped cotton. The total amount of CGT produced for the season is approximately 11,600 tonnes. Electricity and natural gas consumption were simulated for the cotton gin. Historical data from the EIA was used to predict future expenses for the cotton gin for a period of 20 years. Using a conservative estimate of 50 kWh/bale for electricity consumption for the cotton gin a 20 bph rated gin requires a power plant with an output of 1 MW, a 2 MW facility for a 40 bph gin, and a 3 MW facility for a 60 bph gin. It was determined that a FBG unit fueling an ICPP has an estimated capital cost of $1M/MW, while a FBG unit fueling a SPP has a capital cost of $2M/MW. For this economic model a 2 MW rated ICPP and SPP are used with a capital cost of $2M and $4M was used.

Energy expenses consisted of the cotton gin's total electricity and natural gas requirements for the season. Revenue generation was comprised of the money saved from not purchasing electricity or natural gas, along with selling the extra electricity produced from the FBG of the remaining CGT, and biochar sales. Expenses included labor, taxes, insurance, and maintenance for operating the power plants. Operating costs, selling price of electricity and biochar were varied to account for the uncertainties made in the assumptions. The NPVs for the power plants were calculated for each variation and compared to the base assumptions. The selling price of extra electricity resulted in the largest percent change in the NPV for both power plants. A second analysis was conducted to simulate a scenario for the cotton gin where no electricity is available and they must provide their own. In this scenario, there is no source of revenue generation for the power plants. All of the expenses used were the base assumptions to calculate the net cash flows after debt. The average predicted price of purchasing electricity is \$0.10/kWh; the average price to produce electricity for the ICPP is \$0.20/kWh, and \$0.26/kWh for the SPP.

Conclusions

The biochar's PSD and MMD of 34 µm make it an ideal PM to be removed from a gas stream with cyclones. A rotary airlock should be used to introduce PM in a gas stream for testing cyclone performances for reducing high concentrations of PM. Capturing penetrating concentrations of PM from high concentration tests will result in clogging of the filters and lowering the test system's airflow.

The average collection efficiency of the 1D2D and 1D3D cyclone at ambient conditions was 97% for reducing concentrations of biochar from the airstream. Varying the level of biochar concentrations that were introduced to the cyclones did have a significant impact on the cyclone's efficiency. There are no significant correlations between the concentrations of biochar and capture efficiencies. The highest level of capture efficiencies were obtained at the highest loading rate of biochar for both of the cyclones. The average change in pressure drops across the cyclones with air only decreases by 74% for the 1D2D cyclone and by 36% for the 1D3D cyclone when concentrations of biochar are introduced. Further testing of the difference in recorded and calculated pressure drops is needed before changes are made to the TCD method for calculating pressure drops across the cyclones. The reduction in pressure drops across the cyclones when concentrations of biochar were introduced lowers the overall pressure drop of the FBG unit. Further analysis is also needed to determine if the temperatures encountered during gasification will have an effect on the cyclone's performance.

Economic feasibility of the FBG power plants is dependent on the operating costs and the sell back value of the extra electricity produced after ginning season. The NPV of the ICPP is $1,480,000 and the NPV for the SPP is -$160,000 using the base assumptions. The capital costs for the SPP is twice the capital cost of the ICPP. The average price to produce electricity for both power plants, assuming no revenue generation for the twenty year simulation was $0.20 for the ICPP and $0.26 for the SPP. If the current cost of electricity were to increase, the FBG power plants may be feasible with no revenue generation. Further research is necessary to predict the selling price of the extra electricity produced, the operating expenses for the power plants, and the long term effects the penetrating concentrations of biochar will have on the engine and boiler before a 2 MW rated FBG power plant is implemented.

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